Regolith Strength, Water Retention, and Implications for Ripping and Plant Root Growth in Bauxite Mine Restoration

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Abstract

The lateritic bauxite in the Darling Range of Western Australia is approximately 4–6 m deep and is composed of caprock (duricrust) and underlying friable bauxite developed from highly weathered granite and dolerite. This paper investigates the impact of mine floor ripping operations on materials exposed after mining in relation to strength, water retention, and plant root growth. Deep ripping has been shown to create a structured rootzone and increase both recharge and plant available water. Material classified as quartz rich (Zm) lacks structural features for plant root growth, yet the material requires the least force to rip. These materials require deep pre-ripping followed by contour or multi-tine ripping for successful restoration. Materials that contain 50% or more coarse fragments (gravels, cobbles, and stones) increase the force required for pre-ripping operations but only require contour or multi-tine ripping; doleritic clay with a high coarse fragment content may be readily colonized by roots without pre-ripping. Localized compression (smearing) of materials may occur during ripping due to the pre-ripping tine working deeper than its critical depth of 1.0–1.5 m and/or ripping of materials at high moisture content. A relationship exists between the ratio of reactive silica to total silica and the clay content of regolith, both properties being determined from pre-mining borehole samples. This ratio can be used to identify future mine floor materials from borehole data prior to mining and to target ripping operations to appropriate regolith types to enable the most effective and economical restoration practice.

Key words: deep ripping, Jarrah, lateritic bauxite, plant available water, sinker roots, strength.

Introduction

The Darling Range of Western Australia has large deposits of lateritic bauxite which are mined by Alcoa World Alumina Australia (Alcoa). The deeply weathered lateritic profiles have mostly formed from granite or dolerite (Wilde & Low 1980). Mining leaves behind exposed regolith materials that may be dense, hard, structureless, and inhospitable to plant growth. Regolith is defined as all material between rock and the surface (Eggleton 2001). This paper describes water retention, strength, and the impact of ripping on materials left after bauxite mining and plant root growth in response to ripping. It compares bulldozer-measured pressure (strength) with laboratory strength measurements and presents a regolith classification system for use in rehabilitation planning. The outcome for Alcoa of this research is the ability to target ripping practice so that specific techniques can be utilized for each material type. A brief introduction to the geology and plant root growth in the Darling Range and research on ripping techniques is presented below.

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Conflict of Interest Statement: The authors have declared no conflicts of interest.

Darling Range Geology

A typical laterite profile contains a vertical sequence of regolith materials including some or all of the following: rock, saprock, saprolite, plasmic zone, mottled zone or ferruginous saprolite, and lateritic residuum (lateritic duricrust, lateritic gravel) (Eggleton 2001; Anand & Paine 2002; Koch 2007). The mineral composition of granite and dolerite from the Jarrahdale area of Alcoa's mining lease is shown in Table 1. Weathering of minerals in granite and dolerite has resulted in various alteration pathways (Gilkes et al. 1973), and the secondary minerals formed consist mostly of clay (kaolin) and gibbsite (aluminium hydroxide). Chemical alteration of minerals in combination with pedogenic processes involving disaggregation of quartz grains and volume loss (Robertson et al. 1998), the redistribution of clay and silt (Mullins et al. 1987; Lamotte et al. 1997), produce the characteristic clay (plasmic), sandy (arenose), and saprolitic zones within regolith. Cementation by iron oxides also produces hard materials. The alumina-rich (>27.5%) lateritic caprock and mottled zone materials constitute the bauxite ore which is removed during mining (Hickman et al. 1992). Further geochemical and mineralogical characteristics have been described by Anand et al. (1991).

Regolith materials left after mining are diverse and include portions of the mottled zone, clay (plasmic) and

Table 1. The mineralogical composition of granite and dolerite from Jarrahdale Railway crossing, Darling Range, Western Australia.

Mineral	*Formula*	*Volume Percent*
Grantic rocks—Jarrahdale Railway cutting		
Plagioclase feldspar	Abite $NaAlSi_3O_8$ anorthite $CaAl_2Si_2O_8$	46
Alkali feldspar	Orthoclase $KAlSi_3O_8$	26
Quartz	SiO_2	20
Biotite	$K(MgFe)_3(AlSi_3)O_{10}(OH)_2$	6
Magnetite	Fe_3O_4	2
Ilmenite	$FeTiO_3$	Minor
Zircon	$ZrSiO_4$	Minor
Sphene	$CaTiO(SiO_4)$	Minor
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	Minor
Doleritic rocks—Jarrahdale Railway cutting		
Hornblende	$(Ca, Na)_{2\text{-}3}(Mg,Fe,Al)_5Si_6(Si,Al)_2O_{22}(OH)_2$	47
Plagioclase feldspar	Albite $NaAlSi_3O_8$ anorthite $CaAl_2Si_2O_8$	30
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2(Mg,Fe)_3(OH)_6$	10
Quartz	SiO_2	10
Ilmenite	$FeTiO_3$	3

Granitic rocks are dominated by plagioclase and alkali feldspar, quartz, and biotite, whereas hornblende and plagioclase feldspar are dominant in doleritic rocks (Anand and Gilkes 1984*a*; 1984*b*).

sandy (arenose) zones, saprolite, and saprock (Croton & Ainsworth 2007; Koch 2007). A mixture of these materials, sometimes intact and sometimes redistributed during mining and restoration, receive a surface layer of conserved topsoil to form the soil for reestablishment of a sustainable forest ecosystem.

Jarrah Forest Root Systems

The dominant native tree species of undisturbed profiles in the Darling Range is Jarrah (*Eucalyptus marginata*). The root system commonly consists of dense lateral and feeder roots in the top 0.9 m above the caprock and a secondary system at depth (4–15 m) extending from sinker roots in root channels which have penetrated the limited number of cracks and fissures in the caprock (Kimber 1974). Research on the interactions between regolith materials and plant root growth in restored mine pit profiles in the Darling Range is related to maximizing plant growth.

Analysis of dawn water potentials to assess water relationships of naturally growing Jarrah trees and understory species during summer showed that water potentials in shallow rooted plants (roots at <1 m—usually above caprock) decreased rapidly as soils dried. Medium-rooted (1–5 m) and deep-rooted plants (up to 20 m) had similar water potentials throughout the year (Crombie et al. 1988). Seasonal changes in deuterium levels in twig sap, soil, and groundwater were used to determine the sources of water accessed by roots of native Jarrah trees. Results revealed that during May to June at the time of the opening rains (autumn to the start of winter), water extraction by the trees was from 0 to 3 m but was predominantly from 0 to1 m as rainfall increased and winter progressed (Farrington et al. 1996). As the surface layers dry during spring and summer (September to February), Jarrah trees extract water from deeper layers using the sinker roots. Farrington et al. (1996) calculate that 640 mm of water could be accessed during summer from the unsaturated zone above 10 m depth. However, it was not specified if this was the plant available water (PAW) between field capacity (−10 kPa) and permanent wilting point (−1,500 kPa). Dell and Wallace (1983) found that new seasonal root growth recommences each autumn (March, April, and May) following rain and is broadly similar for all types of roots including long roots and surface feeder roots. The framework of fine feeder roots is established during this time. Therefore, the creation of a structured rootzone to enable rapid root growth during autumn and early winter is consequently a primary objective of post-mining ripping strategies.

Early Soil Ripping Research

Early ripping studies conducted in Australia and other countries are generally applicable to the ripping operations conducted by Alcoa. Willatt and Willis (1965) found that the shape of troughs formed by a single narrow tine and the ridge of unripped material between adjacent tines was trapezoidal and the ridge height for unripped material depended on tine depth. Later work examined the pattern of soil fracture in the trough (Godwin and Spoor 1977) and introduced the concept of critical depth with crescent failure above and lateral failure below this depth. Crescent failure occurs when soil of the tine is moved upward and forward and is sheared. Lateral failure occurs as working depth is increased, increasing the aspect ratio (working depth to tine width ratio) so that the soil moves forward and sideways without fracturing or developing a shear plane, thereby causing compression. Shear stresses when smaller than compressive stresses may induce localized compaction instead of fracturing the soil (Stafford &

Geikie 1987). Spoor and Godwin (1978) demonstrated a substantial increase in soil disturbance by the addition of wings to a deep tine.

The design of the ripping implement and regolith material moisture content affect the type of stress created during ripping. Wang and Gee-Clough (1993) using Bangkok clay (55% clay content) at 44% water content (dry basis) showed that a low rake angle induced tensile failure (stress) and as rake angle increased, shear distortion became dominant. Therefore, tine shape and moisture content affect the type and extent of fracture pattern created by ripping, and these variables have important implications for the seasonal timing of the ripping operations on Darling Range bauxite mines. The presence of coarse fragments will also affect the soil fracture pattern. In a soil bin experiment, Studman and Field (1975) used hemispheres to represent coarse fragments with diameters of 1, 5, and 10 cm and found that a minimum coarse fragment size is needed before it will impact on the tine producing a load. The importance of this process in the sometimes gravel and cobble-rich materials of Darling Range bauxite mine floors is presently unknown.

A range of ripping was carried out on Alcoa mine pit floors after soil compaction measurements indicated that ripping to a depth of 1.5 m would relieve all mining-related compaction (Croton & Watson 1987). Refinement of the ripping process has included the introduction of two-stage ripping (pre-ripping and contour or multi-tine ripping), changes to tine shape with addition of wings to the pre-ripping tine and changes in depth and spacing of ripping.

Methods

Impact of Ripping Operations on Materials

Current restoration practice involves battering of the edges of the mine pit and leveling of the surface. The mine pit floor is ripped (pre-ripping) to a depth of 1.5 m and spacing of 1.5 m. Additional leveling is conducted, and overburden and topsoil are returned. A second ripping process (contour ripping) that follows the landscaped mine pit contours uses either a winged tine to a depth of 1.5 m or a multi-tine implement to a depth of 0.8 m and is conducted while seeding. The multi-tine implement is now used for most contour ripping operations (Croton & Ainsworth 2007; Koch 2007).

The assessment of ripped friable material was made by excavating vertical trenches to a depth of 2.5 m. The impact of ripping was assessed by the identification of mine floor regolith, the measurement of the extent of fractured material using simple knife penetration and penetrometer observations, and the determination of the percentage of fractured material. The resulting regolith classification system for the mottled, plasmic, and arenose zones, saprolite, and saprock of lateritic profiles was used to identify materials (Table 2). The dominant regolith types are iron oxide–cemented (Zh), quartz-rich (Zm), and clay-rich (Zp) regolith. These materials are illustrated in Figure 1.

Instrumented Bulldozers

The hydraulic fluid pressure in the tilt cylinders controlling the vertical position of the ripping tine on Komatsu

Table 2. Classification system for lateritic regolith in the Darling Range, Western Australia.

	Class	*Subclass*
Loose or weakly structured materials		
Surface material	Ap1	
Overburden and mixed topsoil and overburden material	Ap2	
Regolith material remaining after bauxite mining		
Mottled quartz rich material	Zm	Zm11/Zm12/Zm13 Zm21/Zm22/Zm23 Zm31/Zm32/Zm33
Pallid clay rich material	Zp	Zp11/Zp12/Zp13 Zp21/Zp22/Zp23 Zp31/Zp32/Zp33
Iron oxide–cemented material	Zh	Zh11/Zh12/Zh13
Prior root channels	Zr	Zr11
Preserved granitic fabric material	Zg	Zg11/Zg12/Zg13 Zg21/Zg22/Zg23 Zg31/Zg32/Zg33
Preserved doleritic fabric material	Zd	Zd11/Zd12/Zd13 Zd21/Zd22/Zd23 Zd31/Zd32/Zd33 Zd31/Zd32/Zd33

The first subclass number indicates increasing clay content from loamy sand to sandy loam (1), sandy clay loam to clay loam (2), and sandy clay (3) in Zm, Zg, Zh, and Zr materials and silty loam (1), silty clay loam (2), and silty clay (3) in Zp and Zd materials. The second subclass number indicates increasing coarse fragment content from 0 to 50% (1), 50 to 80% (2), and greater than 80% (3). Some class and subclass categories dominate and several may be present at any given location (adapted from Kew and Gilkes 2006).

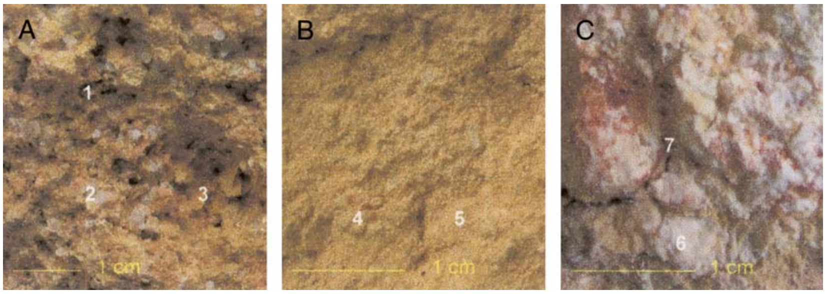

Figure 1. Dominant regolith material types derived from granitoid rocks in the Darling Range, Western Australia. Photograph A shows a cemented red brown iron oxide–rich material (Zh13), with voids (1), quartz (2), and septa (3) (bands of secondary minerals) formed along twinning planes or irregular cracks after weathering of primary minerals. Photograph B shows a quartz-rich (Zm31) material with low macroporosity (no cracks) and abundant quartz (4) in a ferruginous clay matrix (5). Photograph C shows peds of clay-rich material (Zp31) (mostly kaolinite and/or halloysite) (6) with ped faces and cracks occupied by plant roots (7).

475 and Caterpillar D11R bulldozers, fitted with a pre-ripping tine, was measured during ripping operations and provided a measure of regolith strength (Mengler et al. 2006). An increase in draught force on the ripper tine is compensated by an increase in pressure in the tilt cylinder, keeping the tine vertical. Laboratory unconfined compression strength (UCS) measurements were taken on intact samples of regolith material from two pits (Mullian 3 and Chipala 9) and compared to regolith strength maps obtained from the bulldozers.

Regolith Strength and Water Retention Characteristics

Intact clods sampled from trenches at two mine sites (Mullian 3 and Chipala 9) were cut into 2-cm intact cubes with a Boort diamond saw. Forty-four clods representing nine regolith material classes were cut, saturated for 48 hours, and equilibrated at 8 matric potentials (suction levels) using pressure plate equipment (McKenzie et al. 2002) and saturated salt solutions in desiccators. After equilibration at the desired matric potential, UCS was measured using a force gauge. Fracture strength was recorded as the value of strength (kN/m^2) at the first sign of cracking of the cubes, which were then dried and the gravimetric and volumetric water contents determined (Kew and Gilkes 2006). Total porosity was estimated as the percentage of total water at near saturation (i.e., a matric potential of 0 kPa or pF 0). Water retention characteristics of regolith materials were related to regolith exposed in trench profiles to provide an estimate of the PAW at trenches within the mine floor. The topsoils, however, are loose or apedal so that topsoil water retention was determined using the less than 2 mm fraction of topsoil placed in rings on ceramic pressure plates and packed to the same bulk density as in the field.

Prediction of Regolith Using Pre-Mining Borehole Data

Available alumina (Al_2O_3) concentrations greater than 27.5% are considered by Alcoa as economic for mining (Hickman et al. 1992). Samples of regolith material from pre-mining boreholes at a spacing of 15 m and depth increments of 0.5 m are used to develop mining plans. Borehole samples are analyzed using Fourier Transform Infrared (FTIR) spectrometry, microwave digest, and X-ray fluorescence procedures (Eyer 1999). Pre-mining borehole data from Mullian 3 and Chipala 9 were compared with data derived from FTIR of materials classified using the regolith classification system (Kew & Gilkes 2006). The available alumina percentage, reactive silica percentage, total silica percentage, total iron percentage, and the ratio of reactive silica to total silica were used as diagnostic properties to predict regolith material occurring below the mine floor in order to target ripping operations.

Results

Impact of Ripping Operations on Materials

The aim of mine floor ripping operations is to fracture the diverse regolith, creating a structured rootzone in materials that may have high strength, appear structureless, and are hostile to plant root growth. A post-mining profile dominated by quartz-rich (Zm21) material has been fractured to a depth of 1.5 m by a combination of pre-ripping and winged contour ripping (Fig. 2). All materials above the contour ripping depth (CR) have been fractured, and pre-ripping has created artificial root channels (black). A layer of topsoil (Ap1) has been returned to this profile, and unmined regolith and topsoil may be mixed during the ripping process (Ap2).

Excavations at Mullian 3 and Chipala 9 mine pits contained 25–30% topsoil (Ap1) and overburden (Ap2) materials with 50–55% of the final restored profile (to 2.5 m depth) being fractured and disturbed by pre-ripping and contour ripping. The percentage of actual mine floor material that was exposed in the mine pit prior to topsoil return and has now been ripped was 25%. The pre-ripping operation with a straight tine improved the consistency of depth of contour ripping (1.2–1.6 m) when compared to

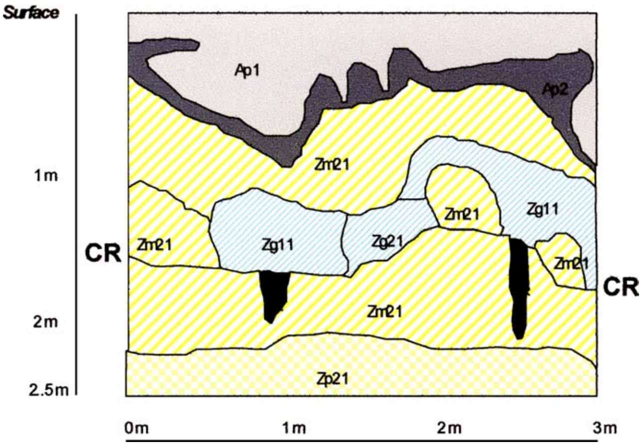

Figure 2. Representative example of a trench diagram showing the spatial distribution of regolith materials, depth of contour ripping (CR), and pre-ripping channels (black). Topsoil (Ap1) is replaced after pre-ripping, and contour ripping may mix topsoil and unmined regolith (Ap2). Zm is quartz-rich material, Zp is clay-rich material, and Zg is preserved granitic fabric material. All materials above the contour ripping line and in the pre-ripping channels will be colonized by plant roots. PAW for each material has been determined and applied to the percentage area of each material to obtain the profile PAW.

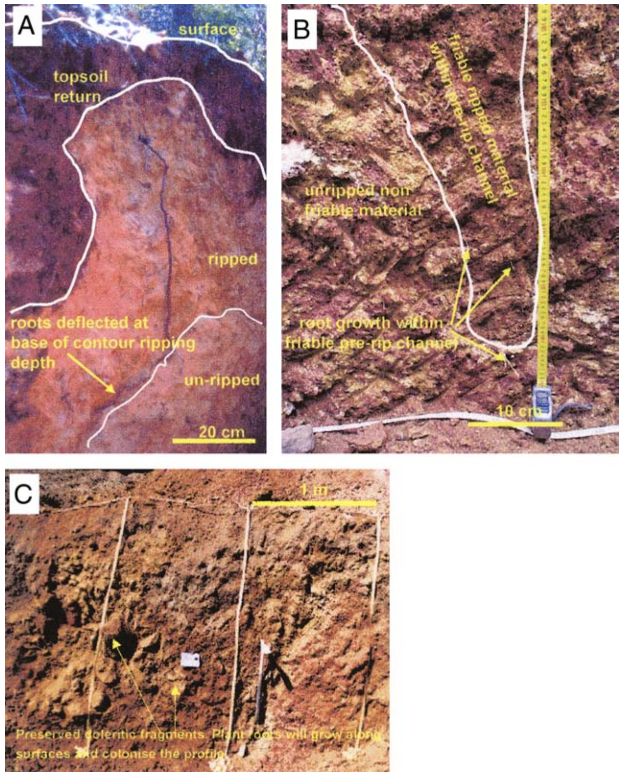

Figure 3. The restored forest on a rehabilitated mine floor at North Road (Huntly) is approximately 16 years old (A). The trench shows restriction of root growth produced by unripped quartz-rich (Zm) material below the depth of the contour ripping operation; no pre-ripping was conducted for this site. Pre-ripping channels in a newly rehabilitated Willowdale mine pit act as root channels so that rapid colonization of the channels occurs after restoration (B). A newly rehabilitated doleritic profile at Chipala 9 mine pit will be rapidly colonized by plant roots that will grow along the interface between coarse fragments and regolith matrix material (C).

a mine pit restored with contour ripping only (0.8–1.2 m). For the regolith types and tine types tested, the critical depth of the pre-ripping tine was determined to be between 1.0 and 1.5 m. The addition of wings to the pre-ripping tine increased the width of the pre-ripping channel from 10 to approximately 30 cm. The use of a multi-tine implement for contour ripping has yet to be evaluated, but anecdotal evidence has indicated that unripped ridges between the tines do not occur, suggesting that the tines are operating above the critical working depth and that all materials to a depth of 0.8 m are completely tilled.

Root Growth of Restored Vegetation

Rapid plant root colonization of topsoil (Ap1 and Ap2) and regolith fractured during ripping is expected following winter rainfall, thus providing stability and erosion control. The regolith material type will influence the success of the ripping operation and the long-term capacity for plant roots to colonize regolith. At North Road mine pit, where contour ripping only was used, roots did not penetrate the unripped quartz-rich (Zm) materials and were restricted by the shallow ripping operation (Fig. 3A). In a pit at Willowdale mine site, plant roots colonized the pre-ripping channel but did not extend into the surrounding regolith (Fig. 3B). In contrast, unrestricted root growth is expected in regolith derived from dolerite which contained 70–90% coarse fragments in a silty clay loam to silty clay textured matrix. Plant roots are expected to grow along the fracture surfaces between coarse fragments and the clay matrix, and this natural structure may not need ripping (Fig. 3C).

A profile at Chipala 9 mine pit after pre-ripping and contour ripping operations shows quartz-rich (Zm) material fractured and disturbed to at least 150 cm depth (Fig. 4). The pre-ripping operation formed a 10-cm-wide channel filled with overburden material although the surrounded quartz-rich (Zm) material remained unripped. Ripped areas were colonized by plant roots, and the pre-ripping channel acted as a root channel analogous to the naturally occurring root channels that exist prior to mining (Fig. 4B). In another profile at Chipala 9, the aligned and permeable pre-ripping and contour ripping channels allowed water to infiltrate and spread horizontally within the angular blocky structured silty clay loam (Zp2) material below the depth of ripping (Fig. 4C). Matric potential was lower within this material.

Regolith Strength Measurements

Regolith materials with high coarse fragment content exhibit high values of bulldozer-measured strength. At

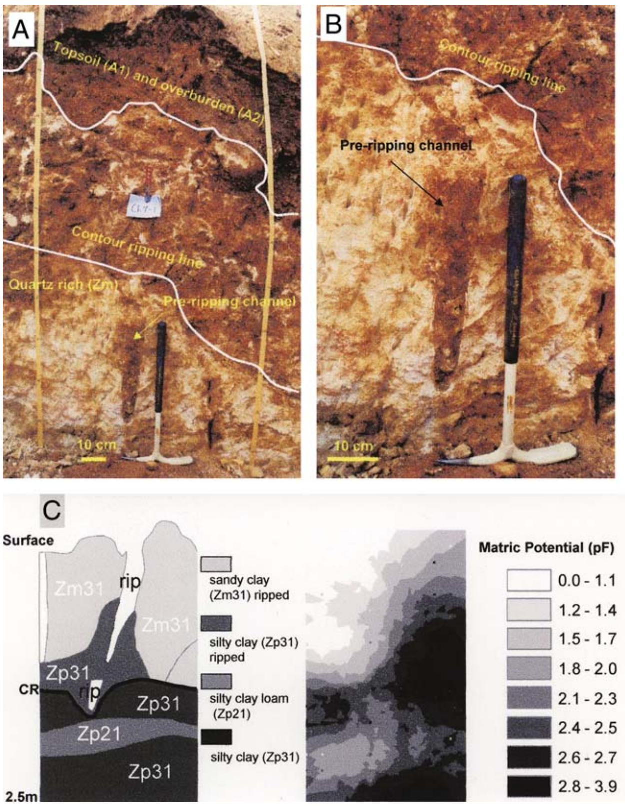

Figure 4. Creation of a friable rootzone above the contour ripping line (photograph A) and a channel created in quartz-rich (Zm) materials that will both be colonized by plant roots (photograph B). Infiltration is high (low matric potential) in the ripped material at another site, and water has been able to spread horizontally within the structured silty clay-rich material below the depth of ripping (C).

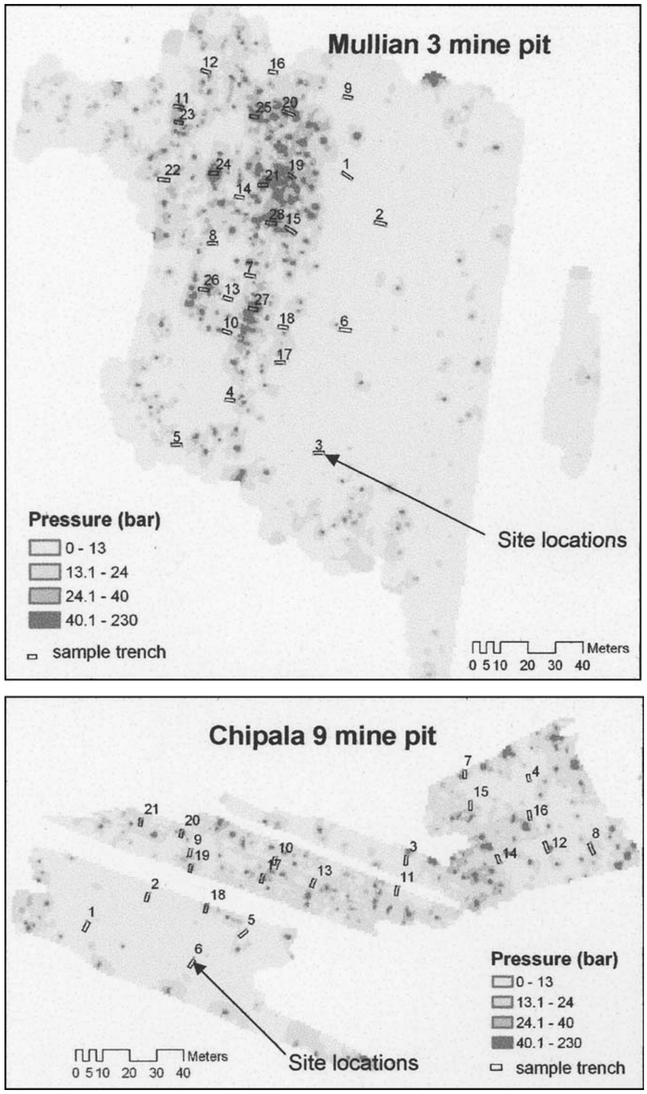

Figure 5. Bulldozer-measured pressure (bars) for Mullian 3 and Chipala 9 mine pits. Light gray represents normal operating pressure in the tilt cylinder between the bulldozer and the ripper, and black represents extreme pressure. Light-gray areas generally correspond to quartz-rich (Zm) materials and are amenable to ripping; black generally represents granite, dolerite or granitic, and/or doleritic saprock, which are resistant to ripping. Intermediate gray areas contain materials with 50% or more coarse fragments (gravel, cobbles, and stones) or dense clay, which are quite resistant to ripping.

Mullian 3 mine pit, extremely high values (40 or more bar) of ripping pressure corresponded to hard saprock (Zg13) near trench sites 15, 19, and 20 (Fig. 5). Values equal to and less than 24 bar (quantile 0.5 or less) operating pressure corresponded to quartz-rich (Zm) materials and moderate, 24–40 bar (quantile 0.5–0.66) operating pressure, corresponded to clay-rich (Zp) materials at Chipala 9 mine pit. Quartz-rich (Zm) material is highly responsive to differences in water content (Kew & Gilkes 2006). Clay slaking during seasonal wetting and drying events produces an apedal or structureless regolith material with lower strength as clay–quartz bonding dominates. The force required during ripping of quartz-rich (Zm) regolith was less than 24 bar, but the apedal structure will require pre-ripping and contour or multi-tine ripping to create a structured rootzone. Clay–clay bonding dominates in clay-rich (Zp) regolith, producing a distinct angular blocky structure that will allow root colonization with minimal ripping even though bulldozer-measured strength was higher than quartz-rich (Zm) regolith.

Laboratory measurements of strength (UCS) at a matric potential of 500 kPa were indicative of the relative force required to fracture various regolith material by ripping in the field although the absolute values of strength are quite different. Median values of UCS for quartz-rich (Zm) regolith were lower than for clay-rich (Zp) regolith, 301 and 367 kN/m^2, respectively. Iron oxide–cemented (Zh) regolith, which includes residual unmined bauxite (gravel, cobble, and stone coarse fragments), is strong (UCS of 2,081 kN/m^2).

The laboratory UCS values determined at 500 kPa have also been applied to the regolith materials in trenches at Mullian 3 and Chipala 9 mine pits. Based on the area of each material within the trench, a weighted UCS value can be determined for the trench and compared to bulldozer-measured pressure (strength) (Fig. 6). Granite and granitic saprock materials had bulldozer-measured pressure values greater than 70 bar, whereas dolerite and doleritic saprock had values between 30 and 70 bar and could not be distinguished from dense clay-rich (Zp) materials. A bulldozer-measured pressure of less than 30 bar may correspond to quartz-rich (Zm), clay-rich (Zp), or iron oxide–cemented (Zh) materials. Thus, bulldozer-measured pressure did not discriminate between all the regolith types but could identify extremes in regolith strength and will enable targeting of ripping operations at sites requiring special remediation treatment.

Water Retention Characteristics of Regolith

Assuming water content at saturation of all pores has a matric potential of pF 0, the total porosity ($/m^3/m^3$) of regolith materials is ranked as: Zp > Zg > Zm > Zh. The silty loam to silty clay textures and low quantities of sand size quartz result in higher total porosity for clay-rich (Zp) materials compared to the grain-supported or matrix-supported quartz-rich (Zm) materials (Fig. 7). The porosity of iron oxide–cemented (Zh) materials and topsoil samples was concentrated in pores greater than 3 μm (upper mesopore range). Approximately 32 and 48% of total porosity correspond to freely drained pores which will not retain water for plants (Table 3). Topsoils also contain up to 65% coarse fragments in the form of pisoliths and nodules, reducing the proportion of total porosity in the plant available range. The pore size distribution showed that granitic and doleritic saprolite with a preserved rock fabric retain 62 and 70% of the water present at saturation beyond wilting point (pF 4.2) so that this large amount of water is unavailable to plants (Fig. 7).

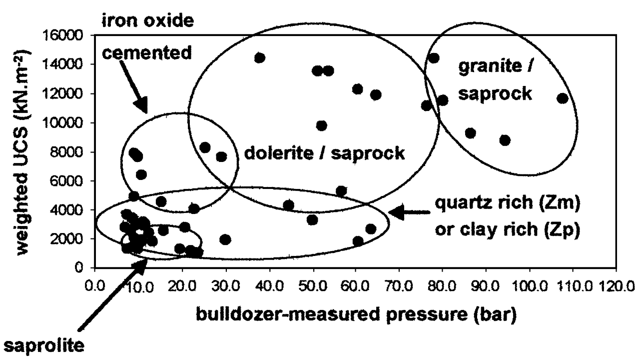

Figure 6. The relationship between weighted UCS from trench diagrams (Fig. 2) and bulldozer-measured pressure. UCS measurements can readily discriminate various regolith materials. Bulldozer-measured pressure (strength) is only partly discriminative with values greater than 70 bar being for granite or saprock; 30–70 bar for dolerite or saprock; and less than 30 bar for quartz-rich, clay-rich, or iron oxide–cemented materials.

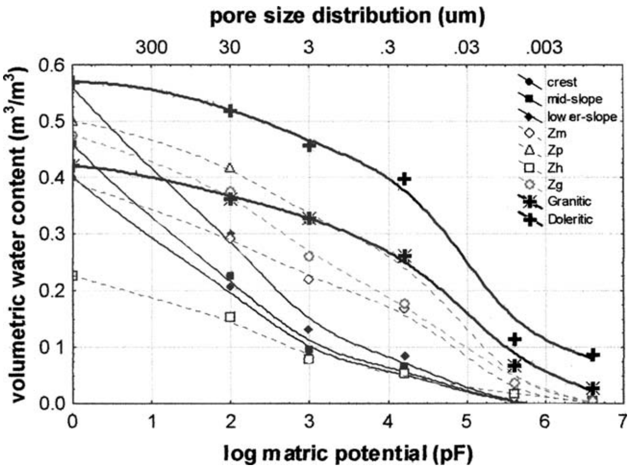

Figure 7. Water retention curves for: topsoil materials (Ap1) from the crest, mid, and lower slopes of ripping furrows created during contour ripping; regolith (Zm, Zp, Zh, and Zg) from Mullian 3 and Chipala 9 mine pits (Huntly mine); and published data for granitic and doleritic pallid zone materials (McCrea et al. 1990). Regolith materials have a higher percentage of total porosity within the PAW range (pF 2.0–4.2), whereas much of the porosity of granitic and doleritic saprolite corresponds to unavailable water (>pF 4.2). Much of the porosity of topsoils is freely draining (pF 0–2).

Application of Water Retention Data to Trench Profiles

Estimates of PAW (field capacity pF 2 to wilting point pF 4.2) for trenches at Mullian 3 and Chipala 9 were made by applying water retention data (Fig. 7) to trench profile descriptions and by excluding the percentage of coarse fragments (material >2 mm). The PAW value for a profile represents the amount of rainfall that can be stored to a depth of 2.5 m and released to plants. Iron oxide–cemented (Zh) material with high coarse fragment content constituted 59% of trench Mu3-4 at Mullian 3, resulting in a low PAW value of 158 mm which might be expected to restrict plant growth. Increased plant growth might be expected at trench Ch9-4 at Chipala 9 where quartz-rich (Zm) material constituted 48% of the profile and has a moderate PAW value of 219 mm and very good growth is expected for the 65% of clay-rich (Zp) material at Ch9-14 with a high PAW value of 304 mm. The average PAW values for trenches excavated at Mullian 3 and Chipala 9 mine pits were 196 and 243 mm, respectively. The lower value at Mullian 3 results from higher percentages of coarse fragments in the regolith compared to clay-rich (Zp) regolith which dominates at Chipala 9.

Classification and Prediction of Materials

The ratio of reactive silica to total silica (ReSi/ST) from analyses of exploration borehole materials was used to predict the distribution of clay in regolith materials in the mine pit. Clay minerals (kaolinite and halloysite) contain the reactive silica determined by FTIR spectrometry. Total silica consists of the silica in clay (reactive silica)

Table 3. Percentages of water held at saturation that is retained at various ranges of pF values for topsoil and regolith materials from Mullian 3 and Chipala 9 mine pits and granitic and doleritic saprolite (McCrea et al. 1990).

	Log Matric Potential (pF)			
Topsoil	*0–2*	*2–3*	*3–4.2*	*>4.2*
Crest	48	30	7	15
Midslope	51	28	7	14
Lower slope	46	30	8	16
Average topsoil	48	29	7	15
	Log Matric Potential (pF)			
Regolith	*0–2*	*2–4.2*	*4.2–6.6*	*>6.6*
Zm1	29	34	35	2
Zm2	27	34	38	1
Zm3	21	27	50	2
Average Zm	26	32	41	2
Zp1	20	35	44	1
Zp2	18	34	47	1
Zp3	11	28	57	4
Average Zp	16	32	49	2
Zh	32	45	22	1
Zg11	21	52	26	1
Zg21	22	32	45	1
Average Zg	22	42	36	1
	Log Matric Potential (pF)			
Saprolite	*0–2*	*2–4.2*	*4.2–6.6*	*>6.6*
Granitic	14	24	56	6
Doleritic	9	21	54	16

Water that will be freely draining and unavailable to plants is represented by porosity in the range pF 0–2; PAW is represented by the range pF 2–4.2; water retained beyond wilting point and unavailable to plants is represented by a pF >4.2. Granitic and doleritic saprolite have much of their porosity in the unavailable range beyond wilting point, whereas other regolith materials contain higher proportions of PAW, and the topsoil has a high proportion of water at saturation that is freely draining.

plus silica in quartz. The ratio of reactive silica (ReSi) to total silica (ST) can, therefore, be used to predict clay content and thus through the classification scheme the strength of regolith materials. Figure 8 shows a schematic diagram of the ratio ReSi/ST in regolith profiles based on pre-mining borehole data. Boreholes are located every 15 m, and vertical intervals in the figure represent a depth of 0.5 m. For example, borehole 2.8 extends 6.5 m below the mine floor. The upper horizontal line represents the original land surface and the lower line the mine floor.

A ratio of ReSi/ST greater than 0.3 indicates a high clay content and usually corresponds to clay-rich (Zp) or doleritic clay (Zd) materials. Doleritic clay (Zd) usually has total iron content greater than 18. A value of 0.1–0.3 indicates sandy clay loam to sandy clay quartz-rich (Zm) materials, and a value less than 0.1 indicates sandy loam quartz-rich (Zm) materials, preserved granitic fabric (Zg) materials, or iron oxide–cemented (Zh) materials. If the ReSi/ST ratio is less than 0.25 and the quartz content is less than 45, then the material is iron oxide cemented (Zh). Therefore, borehole 2.8 was in sandy loam quartz-rich (Zm) material, and boreholes 2.6 and 2.1 contained doleritic clay (Zd) materials which have high iron oxide content. Boreholes 2.7 and 2.5 were in sandy loam quartz-rich (Zm) materials, and boreholes 1.4 and 2.0 showed increasing clay content with depth and contained clay-rich (Zp) material. It is evident that mine floor regolith materials do not occur as discrete strata but as discontinuous bodies as is evident from pits excavated in mine floors (Figs. 2 & 4).

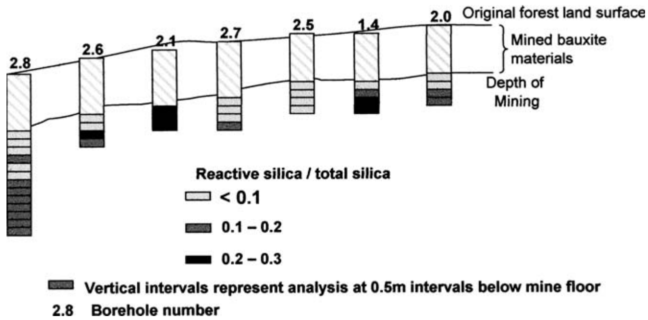

Figure 8. Diagrammatic representation of pre-mining borehole data at 15-m intervals using the ratio of reactive silica to total silica. Borehole 2.8 contains sandy loam quartz-rich (Zm1) material; boreholes 2.6 and 2.1 are in doleritic clay (Zd) as the iron content is high; boreholes 2.7 and 2.5 are sandy loam quartz-rich (Zm1) materials; and boreholes 1.4 and 2.0 show increasing clay content with depth, probably representing pale clay-rich (Zp) material.

Discussion

Impact of Ripping Operations on Regolith

Approximately 25% of the regolith materials left after mining are ripped, and the depth of contour or multi-tine ripping is improved if it follows pre-ripping. At 1.5 m depth, the pre-ripper is operating deeper than its critical depth, which is between 1.0 and 1.5 m. Compressive stresses are greater than shear stresses, and localized compression occurs below the critical depth (Stafford & Geikie 1987) with unaltered material being present adjacent to the ripper (Spoor & Godwin 1978). This pattern of alteration was observed in all regolith materials between 1.0 and 1.5 m when the pre-ripping tine was used. Rajaram and Gee-Clough (1988) observed smearing of material at higher moisture content. As run-off from rainfall events during mining is retained on-site, the moisture content of deeper regolith is high, thus contributing to smearing when the pre-ripping tine is operated at a depth of 1.5 m.

The effects of ripping from this research are relevant to lateritic gold and nickel deposits in Western Australia where regolith materials formed from in situ weathering of rock are exposed after mining. Anand and Paine (2002) give examples of lateritic gold deposits mined to depths of up to 10 m in the Kalgoorlie goldfields region of Western Australia that expose regolith materials in the mine floors. Restoration of mine pits in this region is not sophisticated, and ripping strategies have not been documented in the literature. Deposits of bauxite mined by Worsley Alumina at Boddington in the Darling Range are thick (>5 m), and mine floor regolith is generally not ripped due to deep return of overburden and topsoil materials (M. Braimbridge, personal communication).

The restoration of mined land may result in soil compaction. The aim of deep ripping of shallow mines is the reduction of surface run-off and to increase infiltration (Sweigard & Escobar 1989; Chong & Cowsert 1997). The restoration of surface mines in the United States requires separate replacement of topsoil and subsoil to a minimum depth of 120 cm (Chong & Cowsert 1997). Several authors have detailed the restoration process of surface mines and described a single ripping operation that seldom exceeds the depth of returned materials (Sweigard & Escobar 1989; Chong & Cowsert 1997; Miao & Marrs 2000; Mummey et al. 2002). Materials removed by mining are returned by either trucks or wheeled scarpers, and soil compaction occurs. Ripping is usually within the depth of the returned materials to reduce the soil compaction. However, Alcoa conduct two ripping operations, the first to a depth of 150 cm into unmined regolith and the second to 80 cm within unmined and returned materials. The Alcoa ripping process is unique as unmined regolith materials are ripped prior to return of overburden and topsoil. A second ripping operation which reduces soil compaction from the return of overburden and topsoil is then used in a similar manner to that described for other surface mine restoration projects.

Root Growth of Restored Vegetation

The type of regolith material strongly affects root development and growth of vegetation (Dell et al. 1983). The root occupation of doleritic pallid zone is diffuse in contrast to granitic pallid zone where roots are restricted to channels existing below cracks in the caprock (Dell et al. 1983). Bulk density of the granitic pallid zone is high (1.74 g/cm^3) compared to that of doleritic pallid zone 1.31 g/cm^3 (McCrea et al. 1990). Kew and Gilkes (2006) reported bulk densities of 1.8–1.9 and 1.6–1.8 g/cm^3 for granitic and doleritic regolith, respectively. Differences in root occupancy can be partly explained on the basis of differences in bulk density. Dell et al. (1983) also referred to the coarse blocky fragmented structure of doleritic pallid zone allowing greater root occupation. Ped faces of doleritic materials are readily colonized by plant roots, and therefore, deep (1.5 m) ripping of these materials may not be required. In contrast, Dell et al. (1983) also observed that root growth in restored mine pits, where only contour ripping was used, is restricted to the topsoil return materials and the depth of the "rip fracture zone." Our studies indicate that this observation was probably within granitic quartz-rich (Zm) materials where root growth is restricted to contour ripped materials. In the Darling Range, the combination of pre-ripping and contour or multi-tine ripping is required for quartz-rich (Zm) materials, which lack structure and are apedal.

The growth of Jarrah roots is periodic, occurring predominantly when soil moisture levels are high in winter (Dell & Wallace 1983). Immediately after ripping, fractured material will be loose with a high macroporosity (pores >0.3 mm), enabling wetting of profiles to at least the depth of ripping. The combination of high porosity and elevated soil water content of ripped materials during winter will provide favorable conditions for plant growth.

Regolith Strength Measurements

Studman and Field (1975) in laboratory experiments found that coarse fragments greater than 2 cm in size increase the load on the ripping tine. The abundance and size of coarse fragments were shown to influence ripping force with extreme ripping pressure in granitic saprock and high laboratory UCS for iron oxide–cemented (Zh) regolith. Quartz-rich (Zm) regolith is formed by a combination of in situ isovolumetric weathering and physical alteration (seasonal wetting and drying), resulting in an apedal weak material requiring low ripping pressure to create a structured rootzone. Few fine roots are present in this material in the unripped state.

Classification and Prediction of Regolith

The procedure for predicting mine floor materials based on FTIR analysis of borehole materials has been applied to Mullian 3 and Chipala 9 mine pits to produce regolith material maps. Doleritic clay (Zd), low-Fe content, clay-rich (Zp), and iron oxide–cemented (Zh) regolith materials can be separated based on FTIR analyses. Distinct zones of material are shown on regolith maps, enabling targeted ripping of quartz-rich (Zm) regolith, which lacks structure and is apedal. Plant growth is expected to be greater in clay-rich (Zp and Zd) materials, which have a higher percentage of total water in the plant available range.

Conclusions

Ripped areas have a greater macroporosity due to fragmentation and mixing of materials so that water infiltration and new root growth are higher in ripped materials. The pre-ripping tine does cause some local compression of moist regolith when operated at a depth of 1.0–1.5 m. Weathering of granite has produced quartz-rich (Zm) materials that are generally inhospitable to root growth. Targeting of these materials which require low ripping pressure will increase the percentage of structured rootzone, allowing plant roots easier access to PAW in this material. Clay-rich (Zp) and doleritic (Zd) regoliths have ped faces that are readily colonized by plant roots and require less severe ripping. The high coarse fragment content of iron oxide–cemented (Zh) regolith restricts ripping, but ped faces allow root colonization. The ratio of reactive silica to total silica (ReSi/ST) derived from FTIR analysis of borehole samples used to define the original ore body can be used to identify the clay content of subsequent mine floor regolith materials. Prediction of the clay content, profile PAW, and other properties of regolith materials will enable the planning of ripping operations prior to mining and enhance post-mining restoration success.

Implications for Practice

- Mine pit restoration can be improved by selective identification, targeting, and amelioration of materials. Quartz-rich (Zm) regolith at Alcoa's Huntly mine sites should be targeted by pre-ripping and contour or multi-tine ripping operations. These materials are inhospitable to plant root growth due to a fabric which is dense, hard, and structureless.
- A system of material classification can improve restoration success. The prediction of the clay content, profile PAW, and other properties of regolith materials is possible using the classification system for bauxite mine floor materials developed from this research.
- Mine closure plans can be improved by pre-mining prediction of materials. The prediction of mine floor materials prior to mining based on borehole data will enable targeted ripping and enhance post-mining restoration success.

Acknowledgments

We wish to acknowledge the assistance of Dr. J. M. Koch and Dr. I. J. Colquhoun of Alcoa World Alumina Australia who arranged access to the Huntly mine site and discussed the findings of the research. We also wish to acknowledge funding from Alcoa World Alumina Australia and the Australian Research Council.

LITERATURE CITED

Anand, R. R., and R. J. Gilkes. 1984*a*. The retention of elements in mineral pseudomorphs in lateritic saprolite from granite—a weathering budget. Australian Journal of Soil Science **22:**273–282.

Anand, R. R., and R. J. Gilkes. 1984*b*. Weathering of hornblende, plagioclase and chlorite in metadolerite, Australia. Geoderma **34:** 261–280.

Anand, R. R., R. J. Gilkes, and G. I. D. Roach. 1991. Geochemical and mineralogical characteristics of bauxites, Darling Range, Western Australia. Applied Geochemistry **6:**233–248.

Anand, R. R., and M. Paine. 2002. Regolith geology of the Yilgarn Craton, Western Australia: implications for exploration. Australian Journal of Earth Sciences **49:**3–162.

Chong, S. K., and P. T. Cowsert. 1997. Infiltration in reclaimed mined land ameliorated with deep tillage treatments. Soil and Tillage Research **44:**255–264.

Crombie, D. S., J. T. Tippett, and T. C. Hill. 1988. Dawn water potential and root depth of trees and understory species in south-western Australia. Australian Journal of Botany **26:**621–631.

Croton, J. T., and G. L. Ainsworth. 2007. Development of a winged tine to relieve mining-related soil compaction after bauxite mining on the Darling Range. Restoration Ecology Supplement **15:**S48–S53.

Croton, J. T., and G. D. Watson. 1987. Mining related compaction—a case study in the Darling Range, Western Australia. Environmental Department Alcoa No. 14. Alcoa World Alumina Australia.

Dell, B., J. R. Bartle, and W. H. Tacey. 1983. Root occupation and root channels of jarrah forest subsoils. Australian Journal of Botany **31:**615–627.

Dell, B., and I. M. Wallace. 1983. Periodicity of fine root growth in jarrah (*Eucalyptus marginata Donn* ex Sm.). Australian Journal of Botany **31:**247–254.

Eggleton, R. A. 2001. The regolith glossary. Cooperative Centre for Landscape Evolution and Mineral Exploration, National Capital Printing, Canberra, Australia.

Eyer, S. L. 1999. Estimating bauxite quality using FTIR spectroscopy and multivariate calibration. Research and Development Department, Alcoa of Australia Ltd., Internal publication. Perth, Australia.

Farrington, P., J. V. Turner, and V. Gailitis. 1996. Tracing water uptake by jarrah (*Eucalyptus marginata*) trees using natural abundances of deuterium. Trees **11:**9–15.

Gilkes, R. J., G. Scholtz, and G. M. Dimmock. 1973. Lateritic deep weathering of granite. Journal of Soil Science **24:**523–536.

Godwin, R. J., and G. Spoor. 1977. Soil failure with narrow tines. Journal of Agricultural Engineering Research **22:**213–228.

Hickman, A. H., A. J. Smurthwaite, I. M. Brown, and R. Davy. 1992. Bauxite mineralization in the Darling Range, Western Australia. Geological Survey of Western Australia Report 33.

Kew, G. A., and R. J. Gilkes. 2006. Classification, strength and water retention characteristics of lateritic regolith. Geoderma **136:**184–198.

Kimber, P. C. 1974. The root system of jarrah. W.A. Forest Department Research Paper No. 10.

Koch, J. M. 2007. Alcoa's mining and restoration process in South Western Australia. Restoration Ecology Supplement **15:**S11–S16.

Lamotte, M., A. Bruand, F. X. Humbel, A. J. Herbillon, and M. Rieu. 1997. A hard sandy-loam soil from semi-arid Northern Cameroon: I. Fabric of the groundmass. European Journal of Soil Science **48:** 213–225.

McCrea, A. F., R. R. Anand, and R. J. Gilkes. 1990. Mineralogical and physical properties of lateritic pallid zone materials developed from granite and dolerite. Geoderma **47:**33–57.

McKenzie, N., K. Coughlan, and H. Cresswell. 2002. Soil physical measurement and interpretation for land evaluation. CSIRO Publishing, Melbourne, Australia.

Mengler, F. M., Kew, G. A., Gilkes, R. J., and Koch, J. M. 2006. Using instrumented bulldozers to map spatial variation in the strength of regolith for bauxite mine floor rehabilitation. Soil and Tillage Research **90:**126–144.

Miao, Z., and R. Marrs. 2000. Ecological restoration and land reclamation in open-cast mines in Shanxi Province, China. Journal of Environmental Management **59:**205–215.

Mullins, C. E., A. G. Young, A. G. Bengough, and G. J. Ley. 1987. Hard-setting soils. Land Use Management **3:**79–83.

Mummey, D. L., P. D. Stahl, and J. S. Buyer. 2002. Soil microbiological properties 20 years after surface mine reclamation: spatial analysis of reclaimed and undisturbed sites. Soil Biology and Biochemistry **34:** 1717–1725.

Rajaram, G., and D. Gee-Clough. 1988. Force-distance behaviour of tine implements. Journal of Agricultural Engineering Research **41:**81–98.

Robertson, I. D. M., C. R. M. Butt, and M. A. Chaffee. 1998. Fabric and chemical composition: from parent lithology to regolith. Pages 157–174 in R. A. Eggleton, editor. The state of the regolith. Proceedings of the 2nd Australian Conference on Landscape Evolution and Mineral Exploration. Geological Society of Australia Special Publication 20.

Spoor, G., and R. J. Godwin. 1978. An experimental investigation into the deep loosening of soil by rigid tines. Journal of Agricultural Engineering Research **23:**243–258.

Stafford, J. V., and A. Geikie. 1987. An implement configuration to loosen soil by inducing tensile failure. Soil and Tillage Research **9:**363–376.

Studman, C. J., and J. E. Field. 1975. The motion of a stone embedded in non-cohesive soil disturbed by a moving tine. Journal of Terramechanics **12:**131–147.

Sweigard, R. J., and E. Escobar. 1989. A field investigation into the effectiveness of reclamation equipment alternatives in reducing subsoil compaction. Mining Science and Technology **8:**313–320.

Wang, J., and D. Gee-Clough. 1993. Deformation and failure in wet clay soil: part 2, soil bin experiments. Journal of Agricultural Engineering Research **54:**57–66.

Wilde, S. A., and G. H. Low. 1980. Pinjarra 1:250,000 geological series—explanation notes. Sheet SI/50-2 international index. Geological Survey of Western Australia.

Willatt, S. T., and A. H. Willis. 1965. A study of the trough formed by the passage of tines through soil. Journal of Agricultural Engineering Research **10:**1–4.